Optimal Human Posture—Analysis of a Waitperson Holding a Tray[1]

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ABSTRACT. **This paper explores optimal human posture for burden bearing. The optimization is based upon a uniform muscle stress criterion. This criterion, when used with the governing mechanical equations, removes a redundancy thus enabling a solution of the equations. The paper then presents an application with a waitperson holding a tray. The results are seen to be consistent with observed practices. Implications for dynamic analysis and for optimal performance are discussed.**

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INTRODUCTION

Why does a restaurant waitperson hold his or her tray at eye level, approximately one foot away? Is this simply a convention or is it a convenience for ease of handling and control? Similar and analogous questions are: Why does a lion hold its tail in an upward arch? Why does a giraffe appear to have such a strange galloping gait? Why do many people carry burdens on their heads instead of with their arms? The answers to such questions form starting points for understanding optimal biosystem movement, burden bearing, and control.

Human and animal limbs are kinematically redundant. A given movement of a hand (or foot) may be accomplished with an infinite number of differing arm (leg) and elbow (knee) configurations. For example, a waitperson can hold his or her tray straight out, with the arm fully extended, or close in to the shoulder. Expressed another way, human limbs have more degrees of freedom than needed to accomplish a given task. The extra degrees of freedom provide a means for optimizing the posture for burden bearing and for movement.

In this paper, we propose that uniform muscle stress for the muscles along a load bearing limb is the basis for optimal burden bearing, optimal posture, and optimal movement. If the muscles are uniformly stressed the resulting limb configuration is no longer an arbitrary choice, but instead it is uniquely determined. The governing equations are then no longer redundant but instead they have a unique solution.

The interaction of muscle groups and their respective contributions to burden bearing, posture, and movement have long been a subject of inquiry and research by biomechanicists and ergonomicists. In this regard the works of Alexander (1991 and 1995); Atwater (1979); Zatsiorsky et al. (1981); An et al. (1981); An et al. (1984); Dul et al. (1984); Van Zuylen et al. (1988); Wilson et al. (1991); Cholewicki and McGill (1994); and of Murray et al. (1995) are noteworthy. In the following section we present some experimental data and a rationale for adopting the uniform stress criterion as a basis of muscle interaction for optimal posture and movement.

The subsequent sections present the analysis and the application with the waiter holding a tray. The final section is a discussion with concluding remarks.

UNIFORM STRESS POSTULATE

A classical problem in elementary strength of materials is to determine the shape of a heavy, hanging, load-bearing cable so that the stress is uniform along the length of the cable, as depicted in Fig. 1.

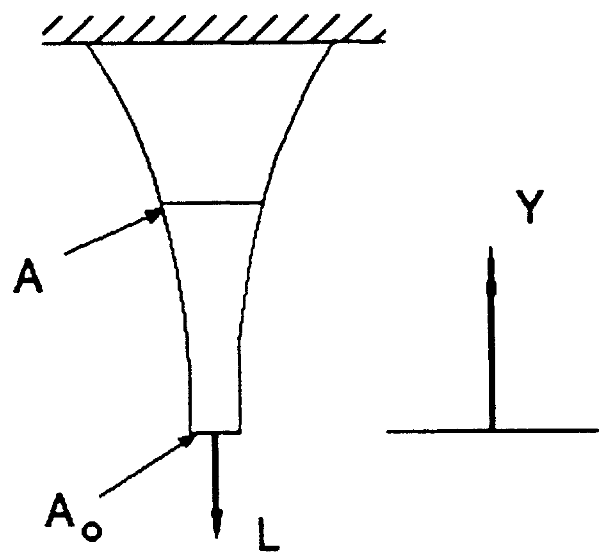

FIGURE 1. A heavy hanging load bearing cable with uniform stress along its axis.

The governing equation determining the cross-section area A and, hence, the cable shape is

$$dA/dy = -(\gamma/\sigma)A \qquad (1)$$

where y is the vertical coordinate, as in Fig. 1, γ is the cable weight density (force/length^3), and σ is the tensile stress (force/length^2)—specified to be constant.

If a load L is supported at the lower end of the cable, the cross section area A_o (as in Fig. 1) at the lower end (y = 0) is then:

$$A_o = L/\sigma \qquad (2)$$

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By solving Equation (1) the cross-section area at any elevation y is found to be

$$A = A_0 e^{\gamma y/\sigma} \tag{3}$$

Interestingly, the cross section areas of the human limbs (legs, arms, and fingers) approximately obey Equation (3). Specifically, the limb cross-section areas obey a relation of the form

$$A = ae^{bx} \tag{4}$$

where a and b are constants and where x is the distance from the hip, shoulder, or first knuckle.

A premise of our analysis is that muscle strength is approximately proportional to the limb cross-section area. This premise was suggested by Professor J. B. Keller in a seminar at Stanford University in 1977. A verification of this premise can be obtained by referring to weight lifting data. To this end, consider that a weight lifter's own weight W is proportional to his or her volume. That is,

$$W = \alpha \ell^3 \tag{5}$$

where α is a constant of proportionality and ℓ is a characteristic length. According to our premise, however, a weight lifter's strength S is proportional to his or her limb cross-section area. That is

$$S = \beta \ell^2 \tag{6}$$

where β is a constant of proportionality. By eliminating ℓ between Equations (5) and (6) we have

$$S = \kappa W^{2/3} \quad \text{or} \quad S/W^{2/3} = \kappa \tag{7}$$

where κ is the constant: $\beta/\alpha^{2/3}$.

Equation (7) can be interpreted as saying that the ratio of a weight lifter's strength (lifting ability) is proportional to his or her own weight raised to the 2/3 power. Alternatively, the ratio of the strength to weight to the two-third power is constant. Table 1 contains data for the average lifts of Olympic winners (see Goetz 1974) during the past 40 years. The ratio of the lift (total for snatch and clean and jerk) to the two-thirds power of the weight lifter's body weight is seen to be nearly constant.

TABLE 1

Weightlifter lifts and lift/weight power ratio for various lifting classes [see Goetz (1974)].

Weightlifter Class Mass (Weight) of the Weightlifter: w [in kg (lb)]	Average Winning Lift*: L [in kg (lb)]	Lift/Weightlifter Mass Ratio $S/W^{2/3}$
55.8 (123)	318.9 (703.0)	28.4
59.9 (132)	333.2 (734.6)	28.3
67.6 (149)	359.0 (791.4)	28.3
74.8 (165)	388.0 (855.4)	28.4
82.6 (182)	405.7 (894.4)	27.9
89.8 (198)	446.6 (984.6)	28.9
109.8 (242)	463.6 (1022.0)	26.3

*Total for Snatch and Clean and Jerk.

ANALYSIS

We can use these concepts to study a waitperson holding a tray. Specifically, consider a free-body diagram of a waitperson's arm as in Fig. 2 where M_1, M_2, and M_3 are joint torques assumed to be developed by the muscles; θ_1, θ_2, and θ_3 are configuration angles as shown; m_1, m_2, and m_3 are the arm segment masses; g is the gravity constant; and L is the load (tray weight).

From the principles of elementary mechanics the governing equations are found to be:

$$M_3 - m_3 g r_3 \cos\theta_3 - L\ell_3 \cos\theta_3 = 0 \tag{8}$$

$$M_2 - M_3 - m_2 g r_2 \cos\theta_2 - (m_3 g + L)\ell_2 \cos\theta_2 = 0 \tag{9}$$

$$M_1 - M_2 - m_1 g r_1 \cos\theta_1 - (m_2 g + m_3 g + L)\ell_1 \cos\theta_1 = 0 \tag{10}$$

where ℓ_1, ℓ_2, and ℓ_3 are the lengths of the upper arm, forearm, and hand, and where r_1, r_2, and r_3 are the distances from the shoulder, elbow, and wrist to the mass centers of the upper arm, forearm, and hand, respectively.

For the waitperson to keep the tray at shoulder level the following constraint equation must be satisfied:

$$\ell_1 \sin\theta_1 + \ell_2 \sin\theta_2 + \ell_3 \sin\theta_3 = 0 \tag{11}$$

From the uniform muscle stress criteria, we see that the joint moments M_1, M_2, and M_3 may be expressed as:

$$M_2 = \kappa A_1, \quad M_2 = \kappa A_2, \quad \text{and} \quad M_3 = \kappa A_3 \tag{12}$$

where A_1, A_2, and A_3 are cross-section areas of the arm at the shoulder, elbow, and wrist.

Equations (8) through (12) form a system of seven nonlinear algebraic equations for the seven unknowns: M_1, M_2, M_3, θ_1, θ_2, θ_3, and κ. This system may be solved by iteration as follows: First, substitute for M_1, M_2, and M_3 from Equations (12) into Equations (8), (9), and (10). Next, solve Equations (8), (9), and (10) for $\cos\theta_1$, $\cos\theta_2$, and $\cos\theta_3$ as:

$$\cos\theta_1 = (\kappa A_1 - \kappa A_2)/[m_1 g r_1 + (m_2 g + m_3 g + L)\ell_1] \tag{13}$$

$$\cos\theta_2 = (\kappa A_2 - \kappa A_3)/[m_2 g r_2 + (m_3 g + L)\ell_2] \tag{14}$$

$$\cos\theta_3 = \kappa A_3/[m_3 g r_3 + L\ell_3] \tag{15}$$

Finally, select a small trial value for κ. Then from Equations (13), (14), and (15) determine $\cos\theta_1$, $\cos\theta_2$, and $\cos\theta_3$, and then θ_1, θ_2, and θ_3. Substitute these results into Equation (11). If Equation (11) is not satisfied, increase κ and repeat the process.

This procedure was used to determine the configuration angles for a waitperson holding 5 and 8 pound (2.27 and 3.63 kg) trays. Fig. 3 shows the results. Table 2

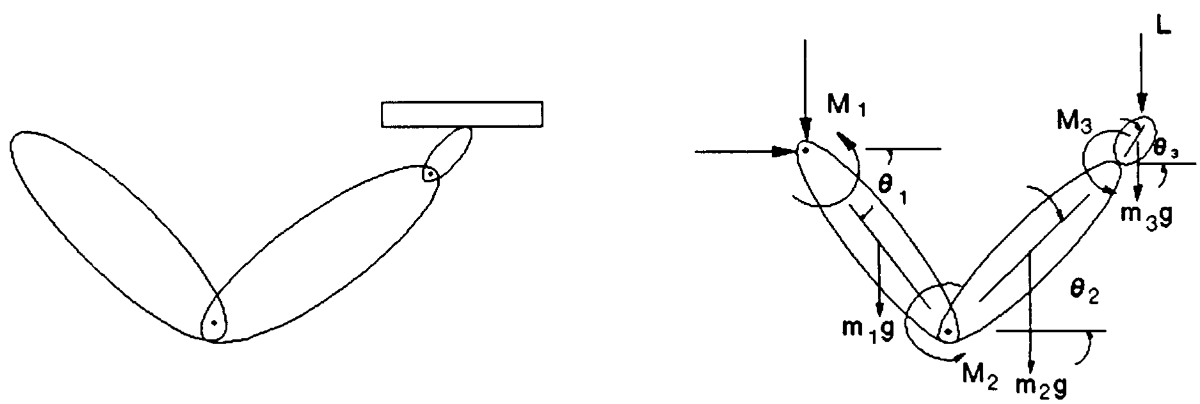

FIGURE 2. Free body diagram of waitperson's arm.

lists the geometrical and physical parameters used in the analysis. (These data are representative of a 50 percentile male waitperson arm.)

DISCUSSION

The procedure and resulting analysis stimulate several comments and conclusion. First, if the results of Fig. 3 are employed in a waitperson drawing we obtain the sketch of Fig. 4. The posture represented is typical of that of a waitperson. Observe the outward bending at the wrist joint.

These results have also been verified using a multibody dynamics simulation computer program called DYNOCOMBS (Huston et al. 1990).

Next, observe that Equations (8) through (11) form a system of four equations for the six unknowns: θ_1, θ_2, θ_3, M_1, M_2, and M_3 Thus, taken alone these equations do not have a unique solution. A unique solution is obtained, however, by imposing the uniform stress criteria of Equations (12), which provide three more equations and one additional unknown κ, for a total of seven equations and seven unknowns.

Finally, consider that the problem examined here is relatively simple, but it is consistent with the approach taken by other investigators (Alexander 1991, 1995; Atwater 1979; and Zatsiorsky et al. 1981). While these investigators do not explicitly use a uniform muscle stress criterion, they use an equivalent criterion with muscle forces decreasing proximally to distally. Indeed, in his review of movement models Alexander (1995) presents persuasive arguments for the use of simple muscle force models.

TABLE 2

Geometrical and physical data for 50 percentile male waitperson arm.

i	r_i [cm (in)]	ℓ_i [cm (in)]	A_i [cm^2 (in^2)]	m_i [kg (lb)]
1. Upper Arm	11.35 (4.47)	29.79 (11.78)	115.5 (17.9)	2.12 (4.68)
2. Forearm	12.89 (5.08)	26.29 (10.35)	51.6 (8.0)	1.23 (2.71)
3. Hand	6.66 (2.62)	6.65 (2.62)	21.9 (3.4)	0.53 (1.18)

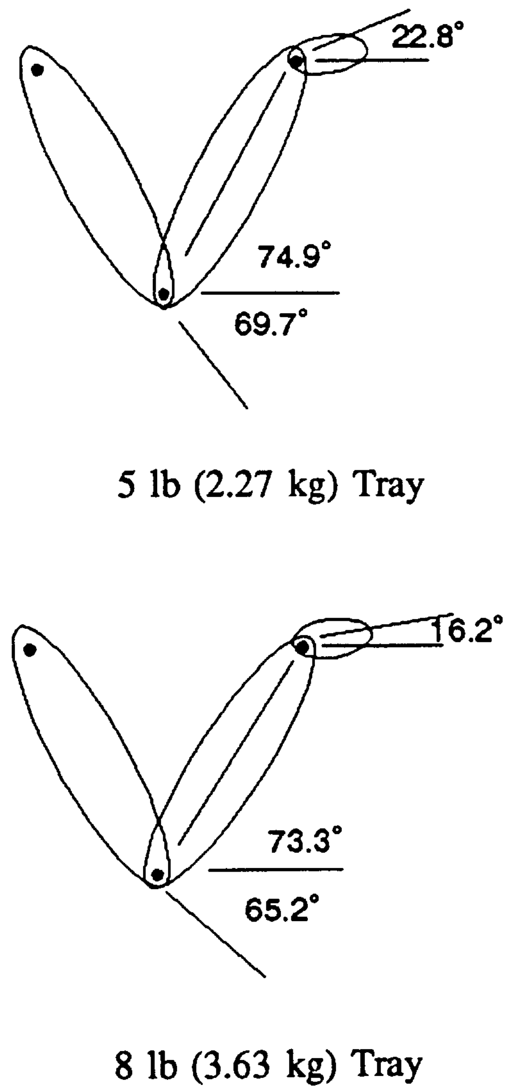

FIGURE 3. Configurations angles for 5 and 8 pound trays.

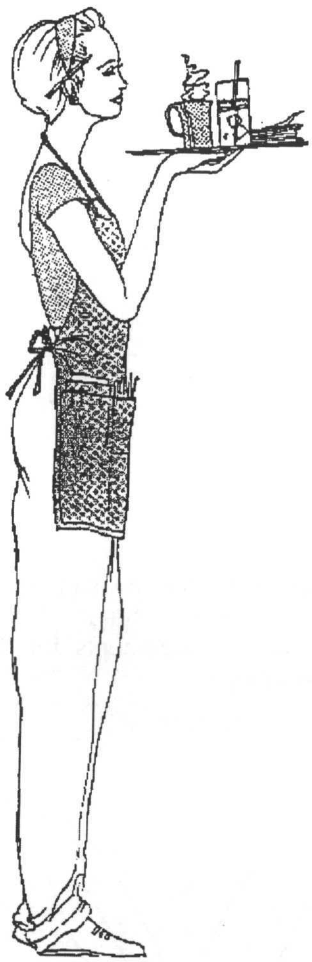

FIGURE 4. Waitperson holding a tray.

The simplicity of the modeling makes it tractable for the analysis of more complex systems such as a lion's tail or an elephant's trunk. Even more significant applications are expected with dynamical systems such as a throwing arm or a kicking leg. Such applications are being planned.

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